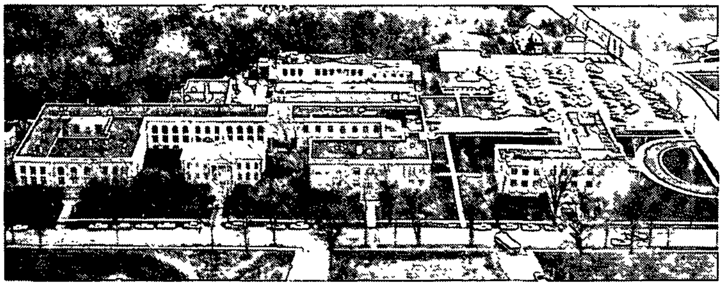

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RELATIONSHIPS BETWEEN RUNNABILITY AND MEDIUM PROPERTIES

WILLIAM J. WHITSITT

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Relationships Between Runnability and Medium Properties

William J. Whitsitt

This work was based on results obtained in IPC Project 3571 and will be presented at the TAPPI Corrugated Container Conference in Chicago on October 25-29, 1987

RELATIONSHIPS BETWEEN RUNNABILITY AND MEDIUM PROPERTIES

William J. Whitsitt
The Institute of Paper Chemistry
P.O. Box 1039
Appleton, WI 54912

ABSTRACT

Based on analysis of the stresses applied to the medium during fluting a physically reasonable model has been developed to show how medium properties affect critical high-low and fracture speeds during corrugating. It may also apply to strength retention. Our analysis accounts for medium properties, flute geometry and the brake tension applied to the medium. The model indicates that speeds causing fracture of the medium increase as the thickness and coefficient of friction of the medium decrease and as the machine direction tensile strength and stretch of the medium increase. Critical speeds for high-low flute formation are affected similarly. The coefficient of friction between the medium and a hot steel surface is an important property and one that is not commonly measured.

INTRODUCTION

Fluting is one of the key elements in the corrugating process. It affects corrugator productivity and the structural performance of corrugated board, and hence affects the cost/performance characteristics of the industry.

During fluting the medium is exposed to tensile and bending stresses which increase with speed. If the stresses are too high, visible fractures occur, resulting in a weak product (1). Before severe fracturing is evident sporadic fractures can be seen on close inspection. This sporadic occurrence reflects medium variability (paper machine formation) and fluctuations in the applied stresses, particularly brake and frictional stresses.

High-low flutes begin to occur with increasing frequency on finger-type machines as corrugating speed is increased. High-lows are influenced by machine condition, operating variables, and medium properties. Because they are strongly affected by speed, it appears they are another manifestation of the response of the medium to high fluting stresses.

Our recent work shows that the MD compressive strength is reduced by 30-40% during fluting, depending on the medium and process (2,3). This decreases flat crush strength. CD compressive strength is degraded by about 20% and the corresponding loss of combined board ECT is about 7%. Reducing these losses would effect significant savings in the manufacture of medium.

As our industry moves to improve end-use medium performance, runnability must be maintained or improved. To achieve this goal, it is necessary to understand what properties of the medium are essential to high speed runnability. The objective of this work is to develop relationships which show how critical corrugating speeds for high-lows, strength, and flute fracture depend on medium properties. These relationships are being used to guide efforts to improve the runnability of mediums and end-use performance.

BACKGROUND

During fluting the medium is drawn into the forming nip, termed the labyrinth. In the labyrinth, the medium is shaped to the flute contour under the prevailing stress, temperature and moisture conditions. At the center of the labyrinth high transverse stresses are applied which reduce the caliper of the medium by about 30% (1). A review of the literature on the stresses imposed on the medium is contained in Ref. (2).

When the tensile stresses due to brake, friction, bending and speed (strain-rate effects) exceed the tensile strength of the medium at the prevailing moisture and temperature conditions in the nip, visible fractures begin to occur. The onset of fracturing manifests itself as decreases in flat crush and greater flat crush variability (1,4). Thus the strength potentials of the medium suffer increasing degradation as speeds approach fracture (5).

Of the operating variables, the medium brake tension is one of the most important. Many investigators have shown that fracturing occurs at progressively lower speeds as the brake tension is increased (1,4,6-8).

Medium moisture content and temperature affect the critical fracture and high-low speed. Most authors agree that low medium moisture content at the roll and in the labyrinth decreases runnability speeds because of the resulting low stretch and high medium stiffness. Several authors suggest that the optimum moisture content at the nip should fall in the range of 6-9% (4,8-10).

Briefly summarizing, the medium is exposed to high tensile and bending stresses during fluting which result in strength degradation, high-lows and, in the limit, flute fracture. While there is information on the general effects of some medium properties and operating variables on runnability, no consistent model which explains the interacting effects of the material, flute design and operating conditions is available. The development of such a model should have great application in optimizing medium manufacture and corrugator operation to improve productivity and quality.

RUNNABILITY MODEL DEVELOPMENT

Our approach to developing a runnability model is based on a physical analysis of the fluting process and has been simplified to permit immediate applications. Empirical constants are used to account for the complex effects of such factors as strain rate, moisture, temperature, and inelastic stresses. Also, corrugators differ in their design, preconditioning, controls and maintenance condition. For this reason the model predictions should be regarded as relative values.

We hypothesize that flute fracture occurs when the induced tensile stresses in the medium exceed the tensile strength of the medium. Note: The model could be formulated in terms of either stress or strain. Accordingly, the following model is proposed:

$$[T_o + S_f/k_1]e^{\mu\theta} + 50k_2T_ft/(R + t/2)\varepsilon = T_f \qquad (1)$$

Rearranging and solving for S_f:

$$S_f = (k_1/e^{\mu\theta})\ [T_f - 50k_2T_ft/(R + t/2)\varepsilon - T_oe^{\mu\theta}] \qquad (2)$$

where T_o = medium brake tension, lb/inch
S_f = fracture speed, fpm
T_f = MD tensile strength, lb/inch
ε = MD stretch, %
t = medium thickness (IPC soft platen method), inches
u = coefficient of hot friction between medium and a steel surface
μ = effective wrap angle in the labyrinth, radians (3.09 radians for the C-flute rolls in our pilot machine)
R = radius of curvature of the flute tip, inches
k_1 = empirical constant = 297
k_2 = empirical constant = 0.0979

In Eq. (1) the factors in the first parenthesis and its multiplier are an estimate of the tensile stresses in the medium due to frictional and speed effects; the factors in the second term estimate the bending stresses during fluting. The tensile stresses due to friction between the medium and the flute tips are dependent on the brake tension, friction coefficient of the medium and flute geometry in the form of the total effective wrap angle in the labyrinth (1,4,9). Speed affects the rate of stressing and the moisture/temperature state of the medium during fluting, both of which affect the properties of the medium. An empirical factor, k_1, is used to adjust the results for speed effects. The tensile strain due to bending is proportional to medium thickness divided by twice the flute radius and is converted to a stress by multiplying by the secant modulus. Thus the tensile stress due to bending is dependent on MD tensile, MD stretch and medium thickness as well as flute tip radius. Summarizing, the fracture speed is dependent on four medium properties, two flute geometry factors and one operating variable, brake tension. Application and testing of the model is discussed in later pages.

The model shows that fracture speeds will increase as tensile strength and stretch increase. Speed will decrease as the friction coefficient and medium thickness increase. Fracture speeds will also increase as the wrap angle and brake tension decrease and the flute tip radius increases. These trends appear to be physically correct.

Flute Profile Factors

A computer program was developed to analyze labyrinth geometry and flute contours. Figure 1 shows the path of the medium in the labyrinth at one instant. The total wrap angle to the centerline would equal the sum of θ_1 through θ_7. However, high speed motion pictures indicate that flute fracture occurs before the medium reaches the centerline, by one-half flute or more (11). Thus it appears that the slippage of the medium over the tips is effectively complete at some point before the center.

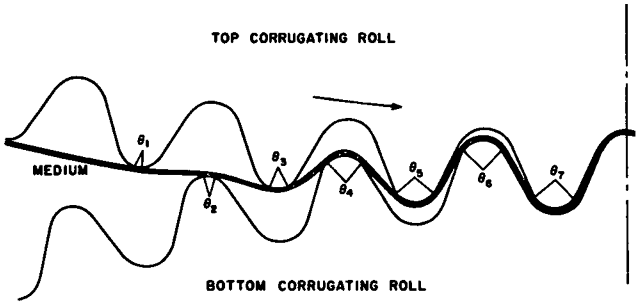

Fig. 1 Path of medium in nip showing progressive increase in wrap angle over flute tips.

Our computer analysis shows that the medium draw is nearly complete at the third or fourth flute tip before the centerline for the C-flute rolls in our pilot corrugator (Fig. 2). These correspond to effective wrap angles of about 3 to 4 radians. Analysis of C-flute fracture data for several mediums indicated that a wrap angle of about 3.09 radians was appropriate for this flute profile. We are currently analyzing other profiles to determine their effective wrap angles.

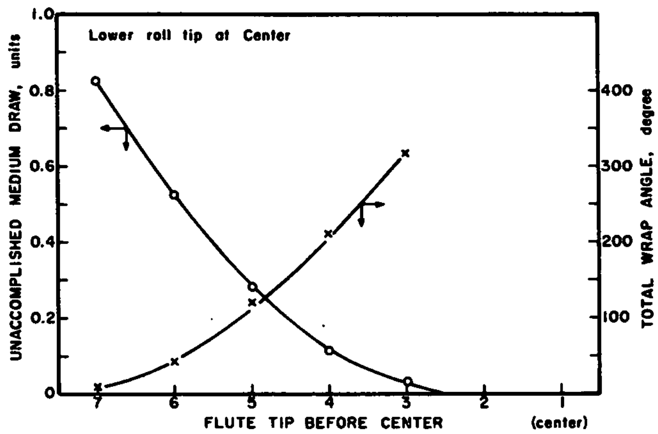

Fig. 2 Unaccomplished draw and total wrap angle as a function of flute tip position in C-flute labyrinth.

Speed Factor

With A-flute rolls, fracture speeds were linearly related to brake tension. Figure 3 shows data for three of the more than 30 mediums tested. Within the precision of the experimental data, the differences in slope between mediums were not statistically different. Recent studies with C-flute rolls gave similar results. For this reason the model was formulated to provide a linear relationship between fracture speeds and brake tension. The relationship is probably more complicated but a more complex function would not provide more understanding at this stage.

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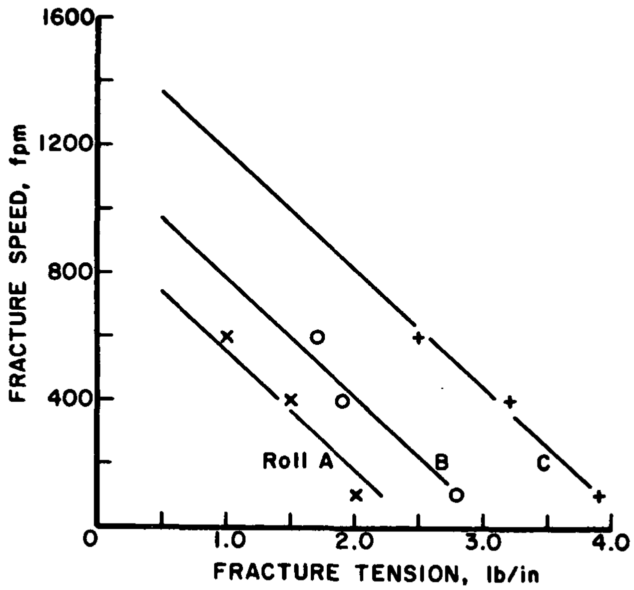

Fig. 3 Fracture speeds are linearly related to brake tension.

Bending Stresses

The second term in Eq. (1) is an estimate of the tensile force induced in the outer layers of the medium due to bending over the flute tip. This approach utilizes the secant modulus to convert strain estimates to tensile stress. Using fracture speed data for mediums corrugated on C-flute rolls, the adjusting constant, k_2, was found to equal 0.0979.

Shear effects were neglected in deriving the bending stress term; however, they may assume greater importance for heavy weight mediums. Compressive strength degradation may also be another factor that should be considered.

Effects of Medium Properties on Flute Fracture

Figures 4-6 show the projected effects of the four medium properties on speeds to flute fracture. In Fig. 4 fracture speed increases with increasing tensile strength and decreasing hot friction coefficient. Figures 5 and 6 show that fracture speeds increase as medium thickness decreases and MD stretch increases at a given hot friction coefficient. These trends seem reasonable based on past experience.

To check on fracture predictions a number of 26-lb mediums were corrugated at speeds up to 1000 fpm on the Institute's pilot single-facer. The mediums were corrugated using controlled but normal preheat and steam shower conditions, and web tensions were varied from 1 to 4 lb/inch to obtain flute fracture if possible. Figure 7 shows that good agreement was obtained between observed and predicted fracture speeds.

From a fracture and high-low standpoint, desirable medium properties include a low friction coefficient and thickness, and high tensile strength and stretch. Better wet pressing which reduces thickness and enhances tensile (and compressive) strength should improve runnability. It will also reduce compressive strength degradation in the fluting process (3). The coefficient of friction varies greatly from medium-to-medium, and it decreases with surface temperature and slowly increases with moisture content. However, preconditioning on the corrugator also reduces the stiffness of the medium as it enters the nip, thus the net effect of preconditioning is a complex balance of several factors.

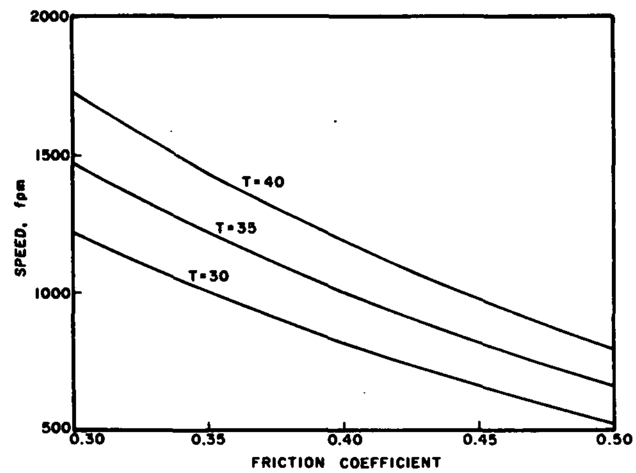

Fig. 4 Fracture speeds increase with increasing MD tensile strength (T) and decreasing hot coefficient of friction.

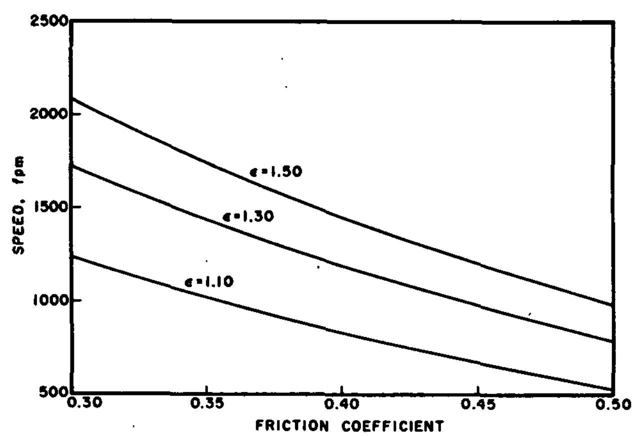

Fig. 5 At a given hot friction coefficient fracture speeds increase as stretch (ε) increases.

To simulate corrugating frictions, the kinetic coefficient of friction between the medium and a clean, replaceable steel foil reference surface is measured. The steel foil is attached to a sled which is heated to about 350°F. The medium is pulled under the sled at a speed of 7.5 fpm. A replaceable steel foil reference surface is used to avoid the difficulties of reproducibly removing contaminants which are left on the foil by the medium. Frequently, residual waxes in the medium are deposited on the steel and act as slip agents to reduce friction. This would also occur during corrugating and can be beneficial to runnability. However, in testing mediums from different sources, such deposits will cause erroneous readings if the surface is not replaced (or carefully cleaned) for each medium lot.

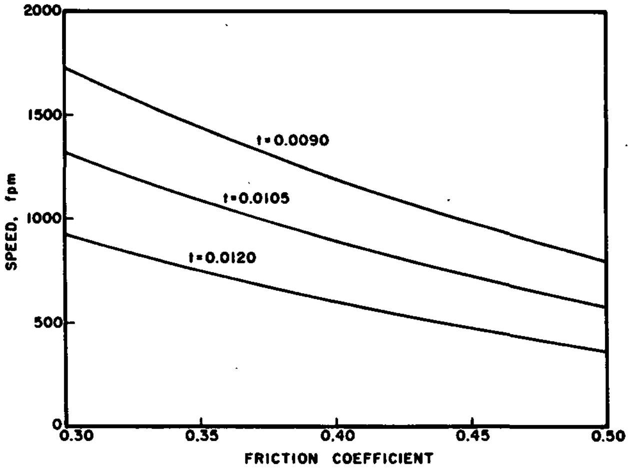

Fig. 6 At a constant friction coefficient fracture speeds increase as medium thickness (t) decreases.

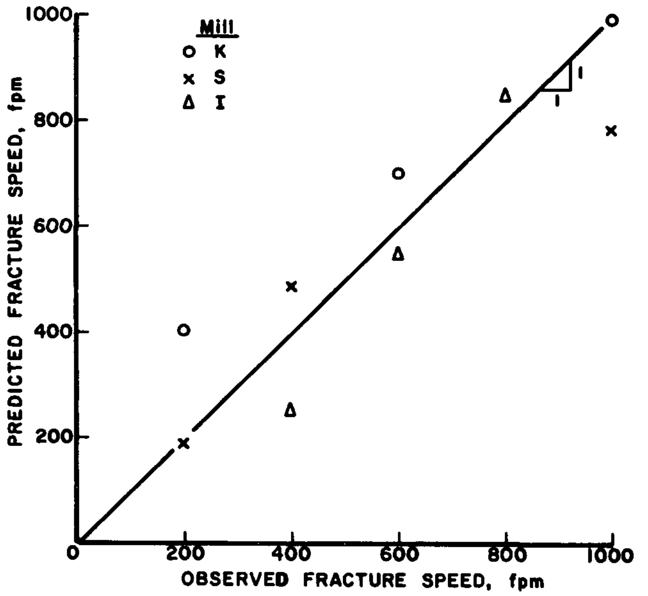

Fig. 7 Observed and predicted fracture speeds are in good agreement.

Most mediums exhibit much lower friction coefficients under hot conditions than at room temperature, and the cold and hot measurements are not well related.

High-Lows

High-lows are a manifestation of form instability, i.e., the medium attempts to relax back to a flat shape but in a nonuniform way. A portion of the strain applied during forming will be recoverable; the remaining portion will be nonrecoverable and contribute to form changes. Both components increase as speed increases. This would explain why high-lows become more pronounced as speed increases (Fig. 8). Also, at high stress levels, local variations in stress and strain which reflect paper-machine formation become more pronounced. These local variations in strain will manifest themselves as high-lows.

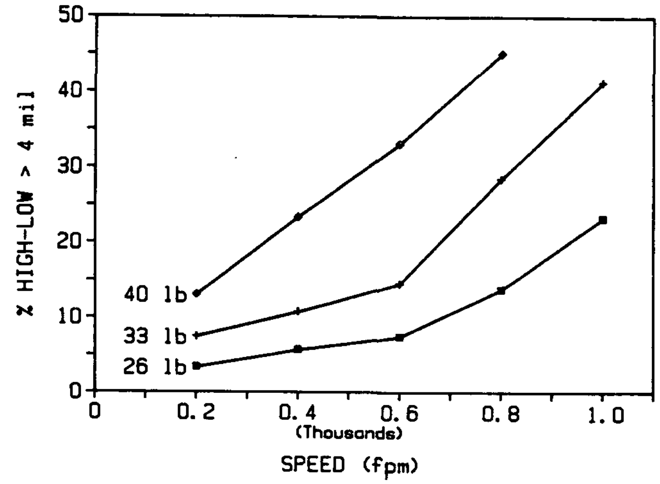

Fig. 8 The incident of high-lows increases with higher corrugator speed and are more pronounced for heavier weight mediums.

From this viewpoint high-low flute formation should depend on the magnitude of the applied tensile stresses. The latter can be estimated using the runnability model.

If the speed, S, is given some value less than the fracture speed, then the left side of Eq. (1) is an estimate of the total applied tensile stresses at that speed. As speed is increased the total stress increases. Fracture occurs when the applied stress exceeds the tensile strength so this becomes the upper limit. Therefore, dividing the applied stress at a given speed by the tensile strength gives a ratio which is a measure of stress severity.

Stress Ratio = Applied Stress/Tensile Strength (3)

To test for high-lows more than 40 commercial 26- and 33-lb mediums were run on the Institute's pilot single-facer at speeds up to 1000 fpm. Controlled but normal heat and steam conditions were used and the medium brake tension was controlled at 1 lb/inch. Samples of the single-faced boards at various speeds were tested using a Selcom laser displacement gage attached to a microcomputer for data processing. High-lows were defined as the percentage of flute height differences exceeding 4 mils.

In Fig. 9 the average high-lows for 26- and 33-lb semichemical mediums are plotted vs. stress ratio. For a given speed the 26-lb mediums exhibit lower stress ratios and high-lows than the 33-lb mediums. When the stress ratios exceed about 0.75-0.80, the curves for both medium weights approximately coincide considering variability and the occurrence of high-lows begins to rapidly increase. Thus mediums with combinations of friction, ten-

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sile, stretch, and thickness which yield lower stress ratios at a given speed should exhibit lower high-lows. Changes in these properties will affect high-lows in the same direction as flute fracture.

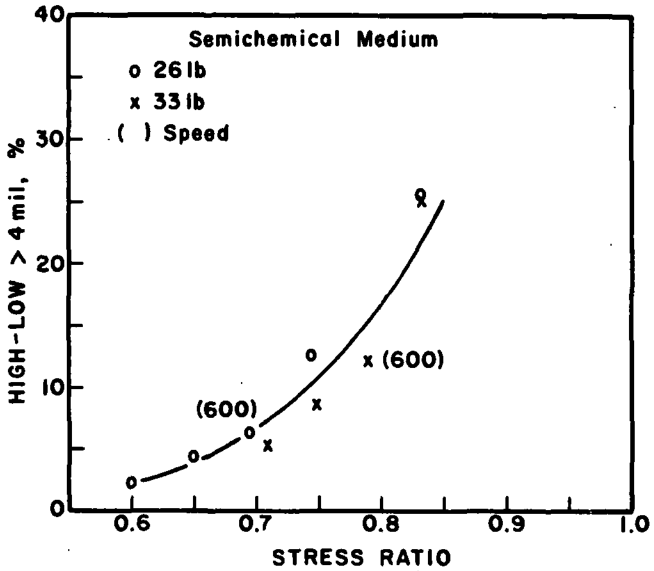

Fig. 9 Greater stress ratios cause more high-lows.

Recycled fiber mediums show a similar relationship between high-lows and stress ratio; however, the average curve is shifted to the left.

High-Low Sensitivity Analysis

Figure 10 shows how changes in test properties affect the speed at which a high-low percentage of 10% is obtained. The base medium with average properties has a speed of 800 fpm. At a constant high-low level changes in stretch and thickness have the greatest effect. Changes in friction and tensile strength have significant but lesser effects than the other two properties. These results illustrate that papermaking factors which give higher stretch and tensile strength and lower friction and thickness will promote operation at higher speed with less high-lows.

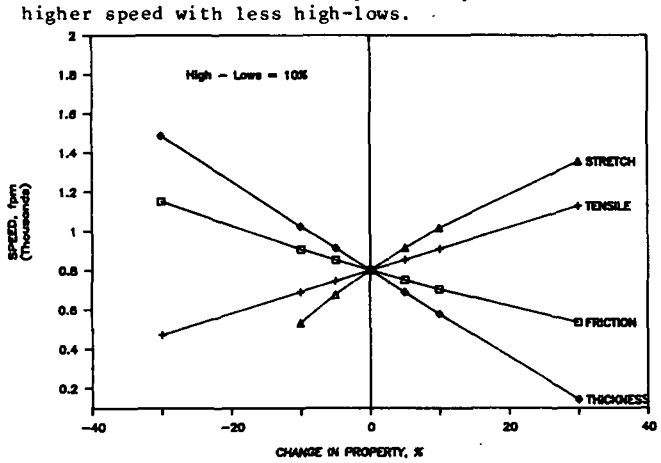

Fig. 10 Effects of changes in medium properties on the corrugator speed resulting in 10% high-lows.

Strength Losses

Our previous work shows that the compressive strength of medium is degraded during fluting (2,3). The tensile strength of the fluted medium is also degraded and Fig. 11 shows that the losses are related to the stress ratio. As the stress ratio approaches unity where fractures are visible, the tensile strength of the fluted medium approaches zero. Note that higher brake tensions increased the stress on the medium and lowered the tensile strength of the fluted medium. Thus the medium suffers increasing degradation under high stresses which can affect combined board performance.

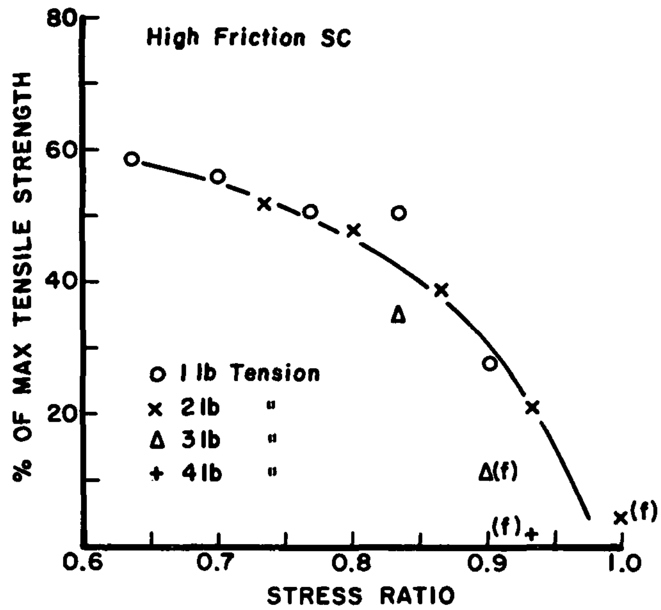

Fig. 11 Tensile strength of fluted medium decays to zero as stress ratio increases.

CONCLUSIONS

(1) A runnability model is proposed which shows that critical speeds for high-lows, strength retention and flute fracture during corrugating are related to medium properties, nip geometry and medium brake tension.

(2) The critical speeds for high-lows and fracture depend on four properties of the medium, namely, MD tensile strength, MD stretch, hot coefficient of friction and thickness. Higher MD tensile and stretch, and lower hot friction and thickness promote higher corrugating speeds without flute fractures and excessive high-lows.

(3) At a constant amount of high-lows, a sensitivity analysis shows that all four properties have significant effects on runnability. However, MD stretch and thickness have greater effects than MD tensile and hot friction.

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